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EXPERIMENTAL STUDY OF THE SHOCK WAVE  
DUE TO A BLUNT LEADING EDGE IN  
THE HYPERSONIC MERGED-FLOW REGIME

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SUMMARY

An experimental investigation of low-density flow over two-dimensional blunt bodies has been conducted in the Langley 1-foot (0.305-meter) hypersonic arc tunnel. Pitot-pressure surveys were obtained over a range of tunnel test conditions with Mach number varying from 11.8 to 13.7, total enthalpy varying from 2.41 MJ/kg to 3.98 MJ/kg, and free-stream Reynolds number varying from  $4.59 \times 10^4$  per meter to  $10.3 \times 10^4$  per meter. The models were cylinders having diameters between 0.05 mm and 11.1 mm and a 1.6-mm-thick flat plate with a leading-edge radius of 0.8 mm. The corresponding range of the viscous interaction parameter  $\bar{V}$  was about 0.175 to 0.82. Transverse-impact-pressure surveys were made from 2 to 55 diameters downstream of the leading edge. All data were obtained in the merged-flow regime and the test data show that even at the highest Reynolds numbers, significant departures from Rankine-Hugoniot shock relations are present.

The density ratio across the shock provides a good test of the departure from Rankine-Hugoniot shock conditions and in the case of the present investigation, this ratio approximately equaled the pitot-pressure ratio. The measurements of pitot-pressure ratio correlated with  $M_\infty \sin \theta / N_{Re,r,\infty}$  (where  $M_\infty$  is the free-stream Mach number,  $N_{Re,r,\infty}$  is the free-stream Reynolds number based on the leading-edge radius, and  $\theta$  is the shock angle). This correlation was used to define quantitatively the conditions for merged flow to occur as well as the magnitude of the departure from the Rankine-Hugoniot pressure ratio.

For the limited enthalpy range investigated, these data indicate no significant enthalpy effect if real-gas calculations are used in evaluating free-stream conditions. The data indicate, in terms of Mach number and Reynolds number, the leading-edge radius at which a body may be considered sharp, that is, the test conditions are defined where the leading edge was sufficiently small so that a measurable shock was not produced. This condition occurred when the cylinder radius was approximately equal to one mean-free-path length.

## INTRODUCTION

With the advent of high-velocity flight through low-density regimes in the atmospheres of neighboring planets as well as high-altitude flight in the earth's atmosphere, a better understanding of rarefied-flow phenomena is needed. The extent of the merged-layer effects on a slender vehicle flying at high altitude has been discussed in reference 1. A review of the overall work in rarefied flow can be found in reference 2. References 3 to 7 describe theoretical analyses of the merged layer on sharp flat plates that use the Navier-Stokes equations, and references 8 to 12 present the results of sharp-flat-plate experimental investigations. Reference 13 shows results of measurements of density profiles in the wake of cylinders, and reference 14 presents measurements of temperature profiles through the shock at the stagnation point of cylinders. These studies represent only a small part of the effort being made in rarefied gas dynamics but they are the ones most closely related to the present investigation.

In rarefied flow, a sharp flat plate generates a wide spectrum of flow regimes and furnishes an appropriate model to examine the effects on the flow-field development due to viscosity. The usual realistic flight case, however, is a body with a finite-leading-edge thickness, and a number of research investigations have had the objective of determining the type of flow regime which develops over the thick leading edge. (However, note that ref. 11 indicates the effects of the leading-edge wedge angle.) One primary question is to determine whether the leading edge is aerodynamically blunt or sharp. A rough guide for determining the flow regime is given in reference 15 and experimental results showing the effects of a flat-faced leading edge with the thickness varying from 1/50 to 4 mean-free-path lengths are discussed in reference 16.

The present investigation was conducted to determine experimentally in terms of Mach number and Reynolds number, the point at which merging begins on the blunt leading edge of a two-dimensional body and to determine as the flow becomes more rarefied the point at which the body might be considered aerodynamically sharp. The reduction in the density jump across the shock, relative to Rankine-Hugoniot values, gives an indication of the degree of flow rarefaction; when the leading edge is so thin that no density jump is induced, the leading edge should be considered aerodynamically sharp. For the data presented, the pitot-pressure ratio immediately across the shock is approximately equal to the density ratio; therefore pitot-pressure measurements are presented.

In the study of the shock shape, it was assumed that a cylinder will produce the same shock as a cylindrically blunted flat plate; the tests with a 1.6-mm-diameter cylinder and 1.6-mm-flat plate tend to confirm this assumption.

The tests were made at Mach numbers from 11.8 to 13.7, free-stream Reynolds numbers from  $4.59 \times 10^4$  per meter to  $10.3 \times 10^4$  per meter, and total enthalpies from

2.41 MJ/kg to 3.98 MJ/kg. The models were four cylinders that were sized to produce Knudsen numbers in the range from 0.07 to 1.0, and a flat plate with a cylindrically blunted leading edge.

# SYMBOLS

C	Chapman-Rubesin coefficient, $\frac{\mu_w}{\mu_\infty} \frac{T_\infty}{T_w}$
d	diameter
H	enthalpy
K	Knudsen number based on free-stream conditions, $\lambda/r$
M	Mach number
$N_{Re}$	Reynolds number
$p_t$	measured pitot pressure
$p_{t,max}$	maximum pitot pressure measured on a flow-field survey
R	gas constant
r	radius
T	temperature
$\bar{V}$	viscous interaction parameter, $M_\infty \sqrt{C/Re_{\infty,x}}$
v	velocity
x	distance from leading edge in free-stream flow direction
y	distance from model center line normal to free-stream flow
$\Delta$	thickness of shock layer
$\theta$	shock angle

$\lambda$  mean-free-path length,  $\sqrt{\frac{\pi}{RT}} \frac{\mu}{\rho}$

$\mu$  coefficient of viscosity

$\rho$  density

Subscripts:

h pitot probe diameter

meas measured

r based on leading-edge radius

s immediately behind shock

t total

w evaluated at wall

x based on length x

$\infty$  free-stream conditions

## EXPERIMENTAL EQUIPMENT AND PROCEDURE

### Test Environment

The tests were conducted in air in the Langley 1-foot (0.305-meter) hypersonic arc tunnel (a description of which can be found in ref. 17). Depending on the test conditions (table I), the usable test core varies in this facility from about one-sixth to one-third of the nozzle exit diameter which is 1 foot (0.305 meter). The tests were made over a Mach number range from 11.8 to 13.7 and a free-stream unit Reynolds number range from  $4.59 \times 10^4$  per meter to  $10.3 \times 10^4$  per meter. The free-stream mean-free-path length varied from 0.127 mm to 0.406 mm. The free-stream conditions were calculated by assuming an equilibrium expansion. A check calculation was made to determine the effects of vibrational nonequilibrium which has been previously measured. (See ref. 18.) Although vibrational nonequilibrium can significantly change the stream Mach number, it only has a small effect on pitot pressure and the ratio of Mach number to

Reynolds number; consequently, for the data presented, the effects of nonequilibrium were negligible.

### Models

The models tested were water-cooled cylinders 0.508 mm, 1.60 mm, 6.35 mm, and 11.1 mm in diameter and a flat plate 1.60 mm thick with a leading-edge radius of 0.8 mm. The models spanned the total diameter of the tunnel section and all measurements were made in the plane perpendicular to the model and including the tunnel center line. All models 6.35 mm in diameter and 11.1 mm in diameter had a pitot orifice in the forward stagnation region.

### Probes

A flat-faced pitot probe with 1.27 mm o.d. and 0.762 mm i.d. was used for the flow-field surveys. The probe was aligned parallel to the center line of the test section. For the models tested, there should not have been enough flow angularity at the locations surveyed to produce appreciable errors in pitot-pressure measurements. The maximum flow angularity encountered in the model flow field at the locations surveyed was always less than  $10^\circ$  and flow angularities of this magnitude have been shown not to affect pitot measurements significantly. (See ref. 19.)

The effects of flow rarefaction on the probe measurements were considered. With Reynolds number based on the probe face diameter, the values of  $M_\infty/\sqrt{N_{Re,\infty,h}}$  varied from 0.9 to 1.4. The data in figure 2 of reference 20 for this range give a variation of  $P_{t,meas}/P_{t,true}$  from about 0.98 to 1.03. A test was made for comparison with the data in reference 20. The probe was mounted in the tunnel along with two other probes of different sizes. Each probe face was at the same tunnel axial location,  $2.54 \times 10^{-2}$  mm from the center line and  $90^\circ$  apart; thus, all probes should have been exposed to the same impact pressure. The variation between probes was in good agreement with that predicted by figure 2 of reference 20. Since  $M/\sqrt{N_{Re}}$ , based on values immediately behind the shock, is less than  $M_\infty/\sqrt{N_{Re,\infty}}$ , the error which is a function of  $M/\sqrt{N_{Re}}$  will not exceed 3 percent. The pitot pressures nearer to the body would have varying corrections depending on the local Mach number and Reynolds number. There was insufficient data from pitot measurements alone to evaluate these local flow conditions; therefore, the data are presented without correction to indicate the general behavior but are not used in the subsequent discussion.

A micrometer traversing mechanism measured the location of the probe to the nearest  $2.54 \times 10^{-2}$  mm. The pressures were measured with an ionization gage having a range of 0 to 30 torr (1 torr =  $133.3 \text{ N/m}^2$  at  $0^\circ \text{ C}$ ) and a manufacturer's quoted accuracy of  $\pm 2$  percent of the reading. The gage output was indicated by a recording oscillograph.

## RESULTS AND DISCUSSION

Deviations from classical continuum flow begin to occur when the free-stream density is reduced to a value where the mean-free-path length becomes appreciable relative to the body size or thickness. Low-density effects become evident when the shock wave and boundary layer merge to form the merged-layer regime. A good indicator for the onset of merging is the decrease in the value of the pitot-pressure jump across the shock compared with the Rankine-Hugoniot prediction. This investigation consists of pitot-pressure surveys of the flow fields about cylinders and a cylindrically blunted flat plate. The coordinate system, model size, and locations surveyed are given in figure 1.

### Flow Field Profiles

The results of some representative surveys are shown in figures 2 and 3. The Rankine-Hugoniot shock theoretically has zero thickness and appears as a discontinuity in the calculated profiles of figures 2 and 3. The dashed curves were calculated by the method of reference 21 by using the real-gas program to evaluate  $\rho v^2$ . In the merged-layer regime, the shock thickness is appreciable and as the flow becomes more rarefied, the shock becomes thicker and weaker until, at a  $K_R \approx 1$ , it is no longer measurable. These effects are illustrated by the profiles shown in figure 2 and typical results are presented for surveys taken 2 diameters back from the leading edge. The Rankine-Hugoniot value of  $p_{t,max}/p_{t,\infty}$  for this case is 4.35 whereas the highest experimental value shown in figure 2 is 2.8 for  $K_R \approx 0.07$ . This value is approximately the lowest value of  $K_R$  at which data were obtained.

Figure 3 shows profiles obtained at approximately a constant  $K_R$  and at different downstream locations for a cylinder and a flat plate. The flat-plate data are at a slightly lower  $K_R$  than the cylinder, and there is a corresponding difference in  $p_t/p_{t,\infty}$  and shock thickness but the location of  $p_{t,max}/p_{t,\infty}$  is the same. The values of  $p_t/p_{t,\infty}$  close to the body are not corrected for changing Mach number and Reynolds number and should not be regarded as accurate.

### Shock-Wave Shape and Strength

The shock-shape prediction for continuum flow over a flat plate with a cylindrical leading edge was calculated by using the technique of reference 21 (an inverse method) and is shown in figure 4. The real-gas solution for a Mach number of 13 was used. The experimental measurements shown for comparison were determined by using the y-distance to the point of maximum pitot pressure  $p_{t,max}$  which might be considered as the approximate inner boundary of the thick shock and should represent the shock shape. Although the shock is made thicker and weaker due to flow rarefaction, the location of



this maximum pressure is well represented by continuum theory, as shown in figures 3 and 4.

The relative shock strength for various values of  $K_r$  at one location is illustrated by the flow-field profiles in figure 2. A measure of the decrease in shock strength is the magnitude of the departure from Rankine-Hugoniot values of  $p_{t,max}/p_{t,\infty}$ . The experimental values of  $p_{t,max}/p_{t,\infty}$  for various values of  $K_r$  as a function of  $x/d$  are compared with the Rankine-Hugoniot predictions in figure 5. At the lower values of  $K_r$ , the data approach the Rankine-Hugoniot values of  $p_{t,max}/p_{t,\infty}$  as  $x/d$  increases. The data shown for  $K_r = 0.25$  were obtained from the flat plate. Data for a cylinder at the same  $K_r$  would be expected to give the same results.

### Onset of Merging

The criterion used in this investigation to determine the onset of merging is the departure of  $p_{t,max}/p_{t,\infty}$  from the predictions of the Rankine-Hugoniot relations. The extent of this departure as a function of Reynolds number and Mach number indicate the degree of low-density effects on flow-field characteristics. According to Hayes and Probstein (ref. 15), the basic parameter for the stagnation region which serves to measure the degree of rarefaction is  $\lambda_s/\Delta$ , where

$$\frac{\lambda_s}{\Delta} \propto \frac{\lambda_\infty}{r} \propto \frac{M_\infty}{N_{Re,r,\infty}}$$

In the case of oblique shocks,  $\frac{M_\infty}{N_{Re,r,\infty}}$  does not correlate the data. The parameter was modified by multiplying by  $\sin \theta$  to give  $\frac{M_\infty \sin \theta}{N_{Re,r,\infty}}$ . This parameter does a reasonable job of correlating the data (as shown in fig. 6) and data scatter seems to be random. The data cover a limited range of flow conditions and shock angles. Further investigation is needed to determine the range of flow conditions and shock angles for which data would be correlated by this parameter.

Figure 6 shows that there is a considerable deviation from Rankine-Hugoniot values of  $p_{t,max}/p_{t,\infty}$  when  $M_\infty \sin \theta / N_{Re,r,\infty} > 0.01$ . Apparently, the onset of merging occurred at a value of  $M_\infty \sin \theta / N_{Re,r,\infty}$  below that for which data were obtained. The shock angle  $\theta$  was measured by using figure 4.

### Blunt to Sharp Transition

When the free-stream mean-free-path length is so large relative to the leading-edge thickness that no pitot-pressure rise occurs, then the leading edge should be considered aerodynamically sharp. At  $M_\infty \sin \theta / N_{Re,r,\infty} \approx 0.3$  (fig. 6), there was no measurable pitot-pressure rise. The leading-edge radius for this condition to occur was

equal to approximately one mean-free-path length, this result is in reasonable agreement with that of reference 2.

Bluntness effects on flat-plate surface pressures are measurable for a leading-edge thickness less than one mean-free-path length (ref. 16). Pitot-pressure ratio or a density ratio across the shock is not so sensitive to slight bluntness as evidenced by the present flow-field measurements in figure 7. These data were obtained with a leading-edge radius of about three mean-free-path lengths. The flagged symbols are data obtained with a cylinder. The data are compared with the sharp flat-plate data of references 7, 9, 11, and 12, and the theories of references 4 and 7 for a sharp flat plate. The agreement with both the sharp flat-plate data and with theory is as good as could be expected if the plate were sharp. The range of the viscous interaction parameter  $\bar{V}$  was about 0.175 to 0.82.

### CONCLUDING REMARKS

An experimental investigation of merged flow over two-dimensional blunt bodies has been conducted in the Langley 1-foot (0.305-meter) hypersonic arc tunnel. Flow-field surveys were obtained over a range of tunnel test conditions with Mach number varying from 11.8 to 13.7, total enthalpy varying from 2.41 MJ/kg to 3.98 MJ/kg, and free-stream Reynolds number varying from  $4.59 \times 10^4$  per meter to  $10.3 \times 10^4$  per meter. The models were cylinders with diameters of 0.05 mm to 11.1 mm and 1.6-mm-thick flat plate with a leading-edge radius of 0.08 mm. The range of the viscous interaction parameter  $\bar{V}$  was about 0.175 to 0.82. Transverse impact pressure surveys were made 2, 4, 11, 14, and 55 diameters downstream of the leading edge.

For a Knudsen number of 0.33 based on the radius, the shock shape is adequately predicted by continuum theory. The flow was found to be merged for values of  $M_\infty \sin \theta / N_{Re,r,\infty}$  greater than about 0.01 (where  $M_\infty$  is the free-stream Mach number,  $N_{Re,r,\infty}$  is the free-stream Reynolds number based on the leading-edge radius, and  $\theta$  is the shock angle).

The leading edge can be considered to be aerodynamically sharp for values of  $M_\infty \sin \theta / N_{Re,\infty}$  above 0.2. A slightly blunted flat-plate leading-edge radius as large as approximately three mean-free-path lengths was found to produce a flow field in good agreement with that of an aerodynamically sharp flat plate.

Langley Research Center,  
National Aeronautics and Space Administration,  
Hampton, Va., August 24, 1970.

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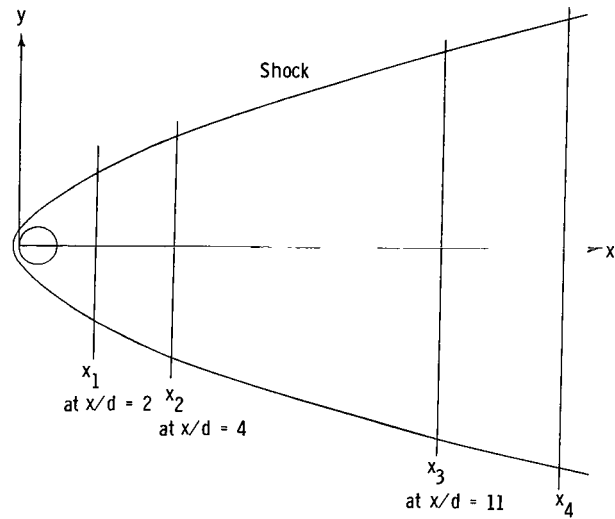
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TABLE I.- TEST CONDITIONS

Test	d, mm	x/d	$p_t/p_{t,\infty}$	$M_\infty$	$H_t$ , MJ/kg	$N_{Re}$ per meter	$N_{Re,r}$
1	0.508	2	1	12.56	3.28	$7.30 \times 10^4$	18.51
2	.508	11	1	11.88	3.36	6.53	16.6
3	1.60	2	1.25	12.58	3.24	6.24	49.5
4	1.60	2	1.25	12.69	2.97	7.20	57.0
5	1.60	4	1.43	12.77	3.05	6.70	53.3
6	1.60	11	1.75	12.53	3.36	5.69	45.2
7	6.35	11	3.02	12.98	3.38	7.16	226.7
8	11.1	2	2.76	12.15	3.98	4.59	254.5
9	11.1	2	2.75	12.96	3.15	8.36	464.3
*10	1.60	11	2.23	13.22	2.58	9.30	73.8
*11	1.60	4	1.58	13.24	2.54	9.60	76.1
*12	6.35	14	3.28	13.53	2.40	10.25	325
*13	1.60	55	2.89	13.69	3.28	6.31	50

\*Flat plate.



Model	Model diameter, mm	$x_1$ , mm	$x_2$ , mm	$x_3$ , mm	$x_4$ , mm
Cylinder	0.508	1.02		5.59	
Cylinder	1.60	3.17	6.34	17.4	
Flat plate	1.60		6.34	17.4	88.8
Cylinder	6.35			69.8	
Flat plate	6.35				
Cylinder	11.1	22.2			88.8

Figure 1.- Coordinate system, model sizes, and locations surveyed.

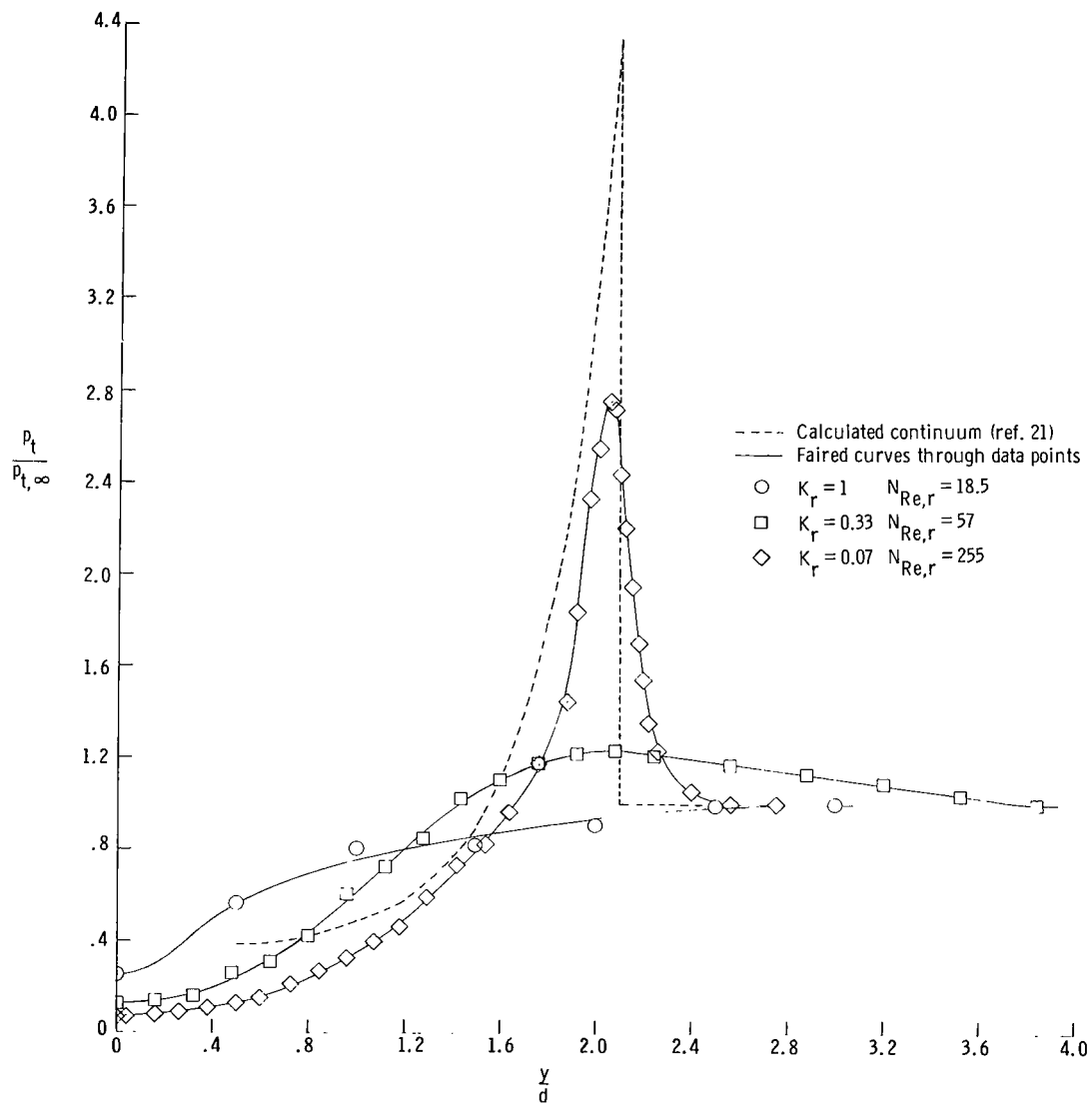


Figure 2.- Flow-field surveys through the shock layer for cylinders  
for various Knudsen numbers at  $x/d = 2$ .

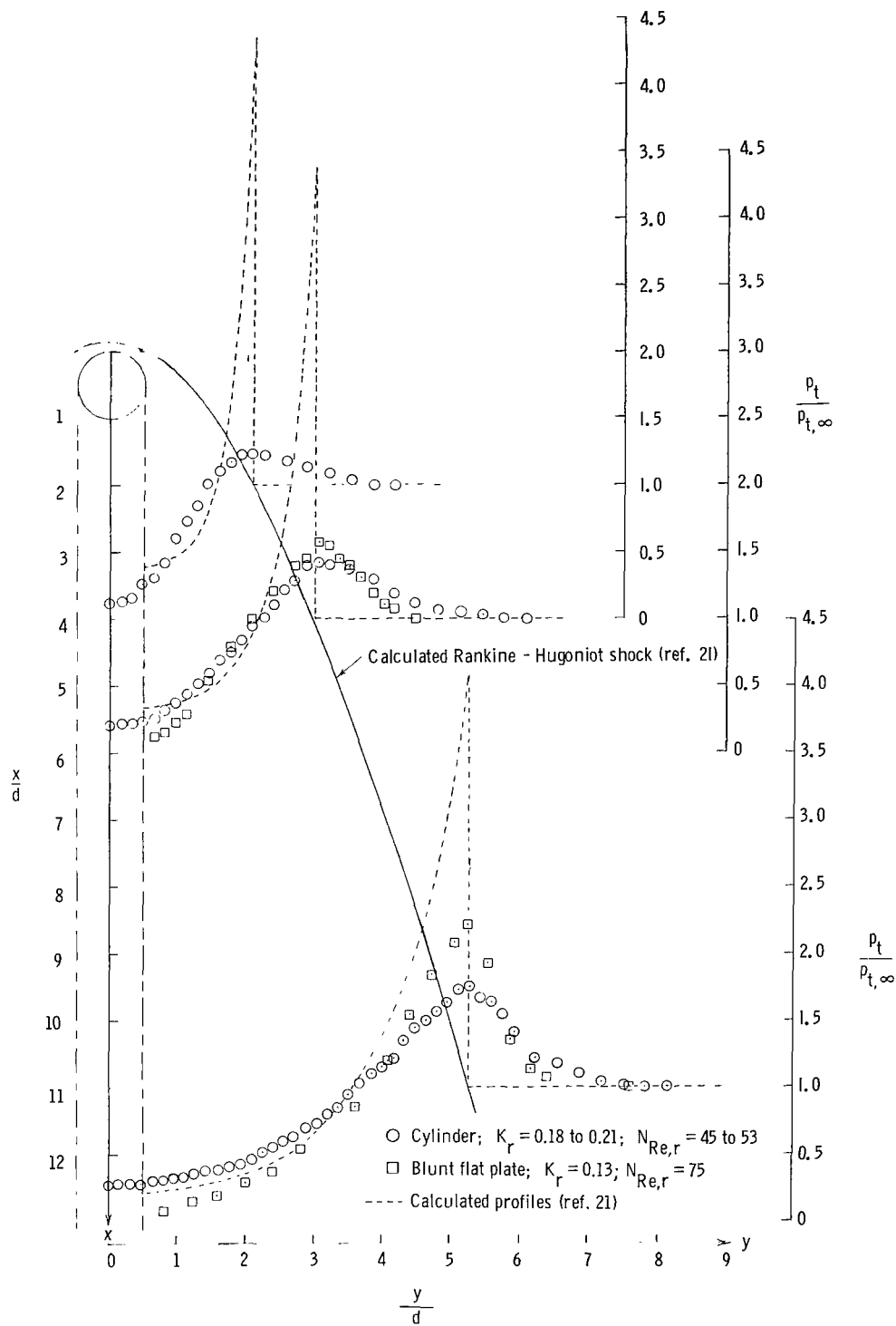


Figure 3.- Flow-field surveys through the shock layer at different  $x$ -locations.  $M_\infty \approx 13$ ;  $p_t \approx 16$  atm;  $T_t = 2200^\circ \text{ K}$  to  $2800^\circ \text{ K}$ .



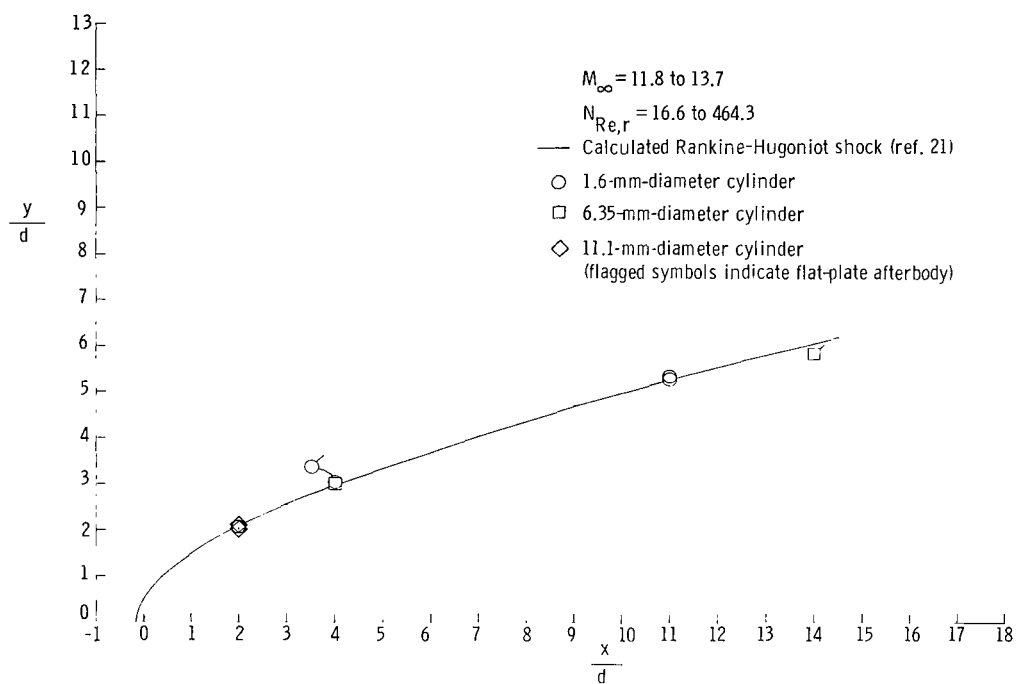


Figure 4.- Comparison of calculated and measured shock shapes.

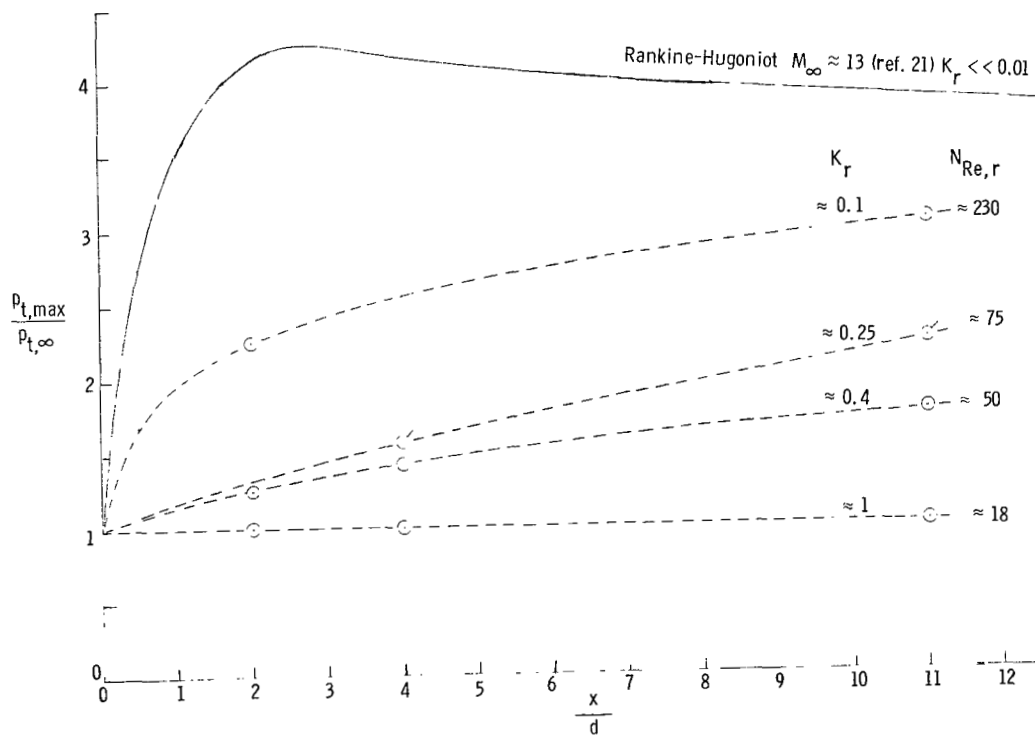


Figure 5.- Variation of impact pressure ratio with  $K_R$  and downstream distance.

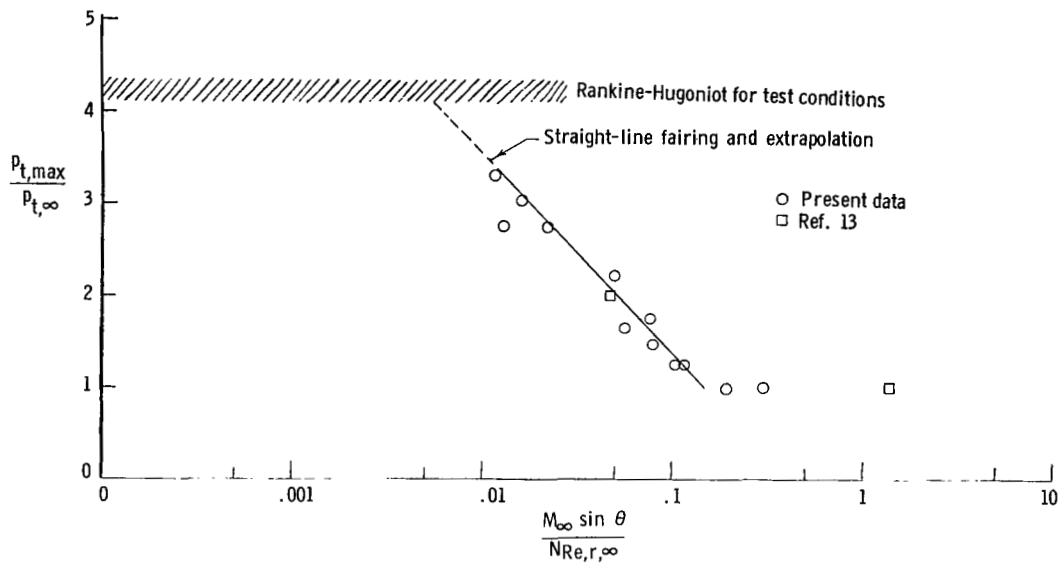


Figure 6.- Correlated pitot-pressure-ratio measurements.

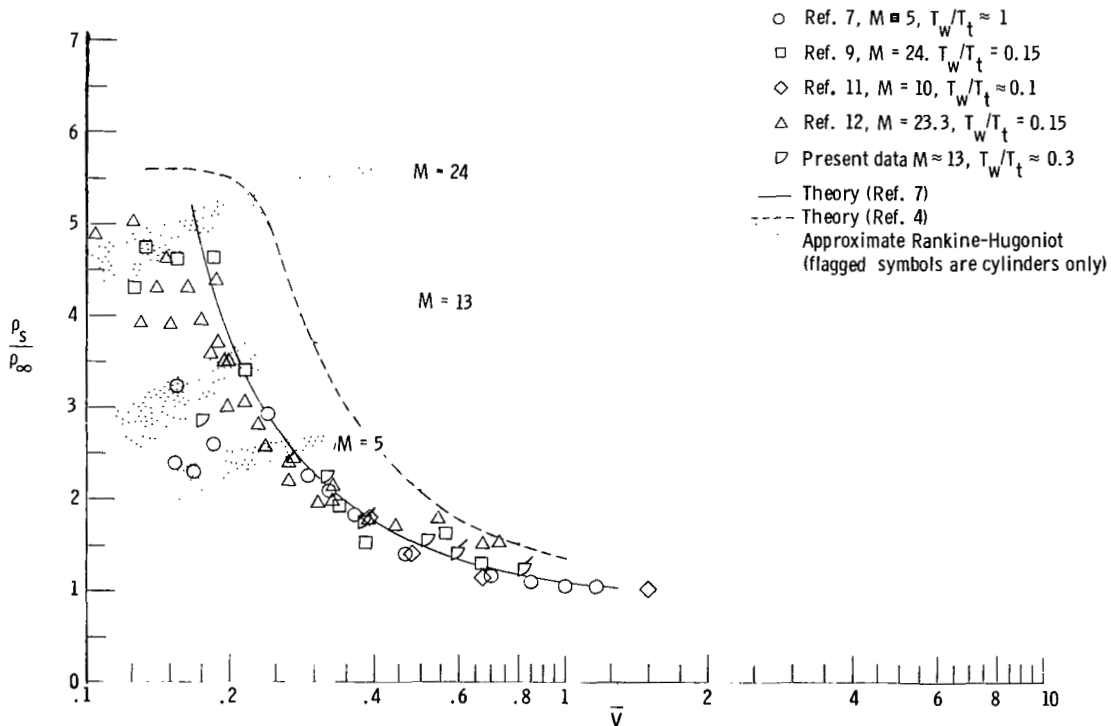


Figure 7.- Density ratio across the shock wave from sharp and blunt two-dimensional bodies in the merged-layer regime.



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